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Squeeze Casting of Aluminum and Aluminum Metal Matrix Composites

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Abstract

The main driving forces for lightweight materials for the automotive industry and military applications are cost effectiveness, high strength, and wear resistance. Precision Metal Forming (PMF) has developed a new and innovative squeeze-casting process called metal compression forming (MCF). MCF integrates the deceptively simple concept of solidification of metal under direct pressure with closed die forging and low-pressure permanent-mold fill technologies. This hybrid process, therefore, combines the advantages of traditional direct-squeeze casting and low-pressure permanent-mold casting. This report discusses property advantages attained with this process over traditional aluminum casting processes.

PREFACE

This is a progress report documenting work carried out as part of a cooperative research and development agreement (CRADA) entitled "Technology and Dual-Use Potential of Squeeze Casting Aluminum (Al) and Aluminum-Reinforced Metal Matrix Composites (Al-MMC) for Both the Automotive and Army Ground Vehicle Applications." This agreement was signed on 25 October 1994, between the U.S. Army Research Laboratory's (ARL's) Materials Directorate (MD) and Precision Metal Forming (PMF). This report covers work through 1 January 1996.

The objective of this CRADA is to formally encourage work toward the development of a database of mechanical and microstructural properties of squeeze-cast Al, which will help determine optimal processing parameters. Research studies are aimed at advancing the state-of-the-art processing of Al-MMCs for advanced Army applications. Metal matrix composites, when compared to matrix alloy, are capable of higher ranges of operating temperatures, and they are tailorable to give improved mechanical and physical properties.

There are two parts to this study. The investigation includes (1) evaluation of the mechanical properties of the Al and Al-MMCs and (2) identification of mechanical-property and microstructural relationships to the processing parameters. Selection of volume reinforcement and heat treatment will be based on initial material properties. Efforts will focus on feasibility of near-net-shape Al and Al-MMCs by the squeeze-casting method, which is currently under development. Extensive evaluation of the mechanical behavior of these materials will be performed, and concurrent metallurgical analysis will be conducted to guide process optimization for maximizing material properties.

ARL has the mechanical testing and microscope equipment necessary to conduct the evaluations. The initial work will consist of testing tensile specimens of Al and Al-MMC with a 10% volume fraction of SiC particulate reinforcement, and as-cast and T6 heat-treatment conditions. Tribological specimens will be tested once the optimal parameters have been determined by the tensile testing. Microstructural characterization will also be conducted on the test coupons after testing to determine grain size, particle distribution, and defects. Upon completion of microstructural characterization and mechanical testing, an effort will be made to determine whether the processing parameters affect the microstructure and mechanical properties.

PMF will provide the tensile coupons and ARL will provide assistance in the determination of the optimal processing parameters for the test matrix.

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1. INTRODUCTION

1.1 Process Introduction. With the constant drive toward cost-effective, high-strength, net-shape casting methods by the transportation industry, Precision Metal Forming (PMF) has developed a new and innovative squeeze-casting process called metal compression forming (MCF). MCF integrates the deceptively simple concept of solidification of metal under direct pressure with closed die forging and low-pressure permanent-mold fill technologies. This hybrid process, therefore, combines the advantages of traditional direct squeeze casting and low-pressure permanent-mold casting.

MCF offers the ability to manufacture high-strength, high-integrity castings for safety-critical applications such as structural and chassis components. The MCF process also represents a more cost-effective alternative to the currently emerging indirect squeeze casting and semisolid forming technologies. Benefits of MCF include reduced capital costs as compared to semisolid forming and indirect squeeze casting, cycle times comparable to cold-chamber die casting, and a "multiple-on" part capability not possible with traditional direct squeeze casting. In addition, MCF offers more flexibility in terms of castability of conventional casting and wrought-aluminum (Al) alloys where isotropic properties and excellent strength-to-weight ratios are necessities.

1.1.1 Process Description. MCF is a hybrid process which combines technologies used in closed-die forging, low-pressure permanent-mold casting, and traditional direct squeeze casting. The MCF process is preferably implemented in a vertical orientation; however, in some cases, horizontal machine orientation may be used. The die design concept parallels that in precision forging of Al alloys where the bottom die is a "finisher" die and the top die is a "blocker" punch. The top die of the MCF process is also a finisher die, but it moves, as does the top die in the precision Al forging process. In the MCF process, the top die, which contains the ejection system, is positioned so that its linear travel will compensate for the solidification shrinkage that occurs during part formation.

The metal-delivery system uses the low-pressure bottom-fill methodology. However, substantial differences exist in the gating design as compared to conventional low-pressure permanent-mold casting. A key difference in the design of the gating system is the hydraulically or thermally activated shut-off pin. The shut-off pin ensures that each cavity has the correct volume of material prior to pressurization. This method has proven to be accurate to within 1% of the required component fill volume, solving a major problem

encountered in traditional direct squeeze casting, which uses metering systems with an accuracy of typically no better than 3%.

The MCF process can be broken down into three steps. (1) top die half is closed to a predetermined position controlled by initial positive stops. This position is an offset determined by the linear travel necessary to compensate for the solidification shrinkage. After the top die half is positioned, the mold cavities are filled with molten alloy via the low-pressure system. As the mold cavities are filled, careful attention is given to thermal management for controlling directional solidification. (2) After the cavities have been filled with the molten alloy, the gate to each of the cavities is closed. In some instances, a vacuum may be applied during the fill stage for evacuation of the cavities. Based on the part geometry, a pressurization dwell time and duration are obtained by closing the top die until the final positive stops are mated. The pressurization duration is typically determined to be equal to or greater than the time necessary for the component temperature to drop below the solidus temperature of the alloy. The pressurization duration is also used for the force feeding of any potential shrinkage cavities. The result is a nearly 100% dense, net-shaped part with an extremely fine microstructure, yielding isotropic properties equaling or exceeding those achieved by precision Al forging. (3) After part formation and the necessary dwell time to achieve ejection temperature, the components are ejected. Part removal and die preparation are similar to those used in conventional die casting. The cycle then repeats to the first step in which the top die half is closed.

1.1.2 Design Considerations. Shape, complexity, size, and section thickness are the principal variables that affect the MCF process and its ability to manufacture a particular component. Achieving detailed features in the part and tooling requires the use of simulation-based design methods to balance the thermal mass and stress patterns in the various casting sections. Process simulation is also used to prevent alloy segregation in alloy systems that have wide freezing ranges.

Certain design rules have been developed for component geometries made using the MCF process. These considerations are presented as follows. The design method must consider the taper requirements, generally 1–2°, for those surfaces in contact with the moving die surfaces. The designer should control the sectional variations such that they are not greater than 1:3:1. Section thicknesses from 0.12 in to 2.5 in are allowable; however, design should optimize heat-flow balance. Dimensional repeatability of ±0.002 in can be used as a design baseline. Most common cast and wrought-Al alloys can be considered for applications using the MCF process. Metal yields are typically better than 90%.

The MCF process offers the ability to form shapes from casting as well as wrought-Al alloys. In casting-alloy compositions the MCF process can typically produce components with substantially better mechanical properties than conventional casting methods. The improvements are a reflection of the fine grain structure, excellent segregation of the particulate reinforcements, and elimination of microporosity. While still under development, the MCF process also exhibits strong potential for forming of wrought-Al alloys (see Table 1). Conventional precision forging achieves mechanical properties that have longitudinal and transverse variations, whereas the MCF process achieves isotropic properties equal to or exceeding those obtained by precision forging. MCF's properties result from the fine cast microstructure produced by pressurized solidification of the wrought-Al alloys.

Table 1. Processing Parameters for A356-T6

Bar No.	Dwell (s)	Pressure (ksi)	Duration (s)	Bar No.	Dwell (s)	Pressure (ksi)	Duration (s)
B-1[a]	5	20	25	Y-1	2	30	25
B-2	5	20	25	Y-2	2	30	25
B-4	5	20	25				
B-5	5	20	25	1-1	2.5	30	25
				1-2	2.5	30	25
C-1[a]	10	20	25				
C-2[a]	10	20	25	2-1	2.5	40	25
C-3	10	20	25	2-2	2.5	40	25
C-4[a]	10	20	25	2-3	2.5	40	25
				2-4	2.5	40	25
G-1	5	30	25				
G-2	5	30	25	3-2[b,c]	2.5	40	25
G-3	5	30	25				
				4-1[b]	2.5	40	40
X-1[a]	3	30	25				
X-1[a]	3	30	25	5-1[d]	2.5	40	40

[a] Shrinkage pores at the grip area.
[b] Adv. densifier by 0.007 in.
[c] Specimen broke in shoulder.
[d] Adv. densifier by 0.0015 in total.

As with indirect squeeze casting and semisolid forming, tooling design for the MCF process can present problems if strict engineering principles of heat and stress management are not employed. The pressure which solidifies the Al alloy can have a significant effect on certain die geometries. This impact, which is caused by constant contact at the interface between the Al and the tool steel, can promote thermal fatigue in the tool steel. Composite die designs with inserts and temperature-control passages are therefore used in the MCF process to prevent initiation of thermal fatigue. Studies have shown that inserts with moderately complex geometries will have lifetimes of 40,000–50,000 cycles.

Research and development are currently being performed to enhance die life for the MCF process. Two current areas of research are the use of die materials with higher thermal-conductivity values and the electrostatic application of the die-release agent. Both areas are expected to yield extended tool life by reducing cyclic thermal shock. In summary, intelligent tool design is required to amplify the advantages of the MCF process without comprising performance or economics.

1.1.3 Capital Investment. The MCF process uses standard foundry equipment and raw materials which support conventional die casting and low-pressure permanent-mold casting. The MCF process, typically engineered in a vertical orientation, uses a machine capital cost comparable to that of cold-chamber die casting. MCF uses the benchmark of approximately $1,000 for each ton of hydraulic clamping force required. MCF pressures and associated clamping-force requirements are determined using the simple ratio of (load/projected area) for the component shape. Tall, slender components require higher pressure than those that have a lower aspect ratio. The overall pressure range will always be considerably lower than that found in the precision forging and conventional die casting of Al alloys. The reduction in clamping-force requirement can, therefore, be translated into lower machine cost and/or increased "part-on" capability.

MCF machine amortization is further enhanced by shorter cycle times than those exemplified in the indirect squeeze-casting process. Overall, the MCF process is considerably more economic than the alternatives of indirect squeeze casting and semisolid forming.

1.1.4 Typical Applications. Historically, wrought products have been employed where strength and structural integrity are important, whereas castings have been employed in areas where structural strength is less critical and where shape capabilities of the casting process can be used to economic advantage. The MCF process can be used to form a wide variety of metals into near-net-shape and net-shape components. Some of the advantages of the MCF process include the ability to use noncasting alloys, dimensional accuracy and

repeatability, and reduced machining and inspection costs. The parts can also have mechanical properties characteristic of forged products with porosity-free microstructures and isotropic properties. Also, the production rate is comparable to conventional cold-chamber die casting, and designers can incorporate a wide range of ferrous inserts and/or composite structures for localized property enhancement.

The MCF process is quickly becoming an established method in the next generation of metal-forming techniques for the transportation industry. As has been presented in this report, the MCF process represents a more cost-effective alternative for the currently emerging indirect squeeze-casting and semisolid forming technologies. The MCF process also offers more flexibility in terms of castability of cast and wrought-Al alloys where isotropic properties and excellent strength-to-weight ratios are a necessity.

1.2 History. Upon receipt of the Cooperative Research and development Agreement (CRADA), Thompson Aluminum Casting (TAC) proposed to perform the test program at a test site located in Marion, OH. The basis for locating the test site in Marion was to be in close proximity to the manufacturer of the squeeze-casting press so that any problems or difficulties with the equipment could be easily addressed. TAC then formed a separate company known as PMF in order to avoid confusion with their main plant for the sole purpose of testing and advancing the squeeze-casting process.

Unfortunately, Marion did not have a suitable infrastructure to support the test program. All support had to come from the main plant located in Cleveland, including sparking the metal on a spectrograph. The only spectrograph located in Marion belongs to Marion Steel, and all of their channels were for ferrous alloys. Other items required to advance the test program were also lacking, causing PMF to rely continually upon and transport items from the Cleveland main plant.

In late 1994, a corporate decision to relocate the test site back to Cleveland was made. A moving team very familiar with moving heavy industrial equipment was retained, and the move was completed in early March 1995. Once in the new location, the local electric company was unable to connect the new test site with a 480-V electrical service necessary for operating the machinery. This caused considerable delay as the squeeze-casting machine was ready for shipment in early 1995, and debugging from the move could not begin until June 1995 because of the lack of a 480-V service. Machine debugging began and certain problems were found, including damage to some of the resistance heater coils on the furnace. These problems were corrected during June 1995.

It was also determined that some changes to the overall concept for squeeze casting would be needed in order to fully exploit the full production capability for this type of process. In January 1995, work began on the engineering of the next generation of closed die direct squeeze-casting tooling for Al and Al metal matrix composite (MMC) test geometries. The intention was to utilize the downtime required for the relocation of operations to Cleveland as a scheduling window. The engineering, machining, and construction of the new tooling was completed on schedule in March 1995. However, since the electrical service had not been installed, debugging of the tooling was delayed until June 1995.

Testing and debugging of the new tooling began immediately after installation of the electrical service. An analysis resulted in the identification of three problem areas. First, the travel distance of the squeeze needed to be adjusted to incorporate a correction factor for displacement of metal through the venting of the cavity. The second problem area was that the stroke of the cylinder controlling the shut-off pin produced misalignment of the moveable portion of the die. Due to an incorrect calculation by the tooling vendor on the interference dimensions of the shut-off pin, the die cylinder had to be relieved an additional 0.350 in. The third problem was directly caused by the overextension of the shut-off pin, which resulted in misalignment of the guide pins. These problems were eliminated in early August 1995.

Since early August, the machine and die fixtures have been operating in a repeatable manner. Work between August and September 1995 has resulted in the identification of operating process parameters for the production of sound metallurgical test geometries.

The U.S. Army Research Laboratory (ARL) Materials Directorate (MD) also experienced significant downtime due to the lab relocation from Watertown, MA, and Aberdeen Proving Ground (APG), Maryland, to Chestnut Run, DE, in 1995.

1.3 Microstructural Characterization. The microstructural characterization was done using the National Institutes of Health (NIH) image analysis program to calculate volume percent of reinforcement in the micrographs, shown in Figures 1–3. The A356 specimens were etched with Keller's reagent, which is a mix of 2-ml HF, 3-ml HCl, 5-ml HNO3, and 190-ml H2O. The A359 MMC specimens were etched with Poulton's reagent, which consists of 12-ml HCL, 6-ml HNO3, 1-ml HF, 20-ml H_2O, and then were stained with CrO_3 and H_2O solution.

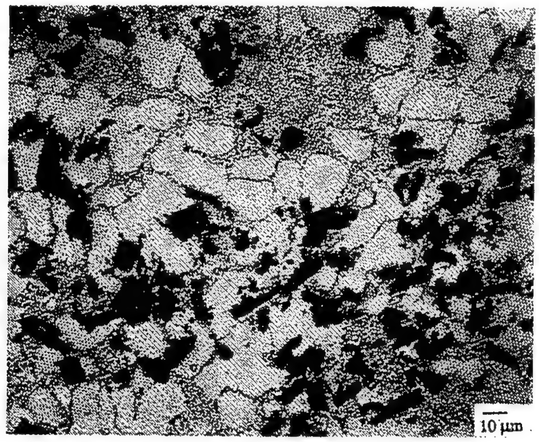

Figure 1. A359 No. 12 optical micrograph showing about 18 vol. percentage SiC reinforcement at 500×.

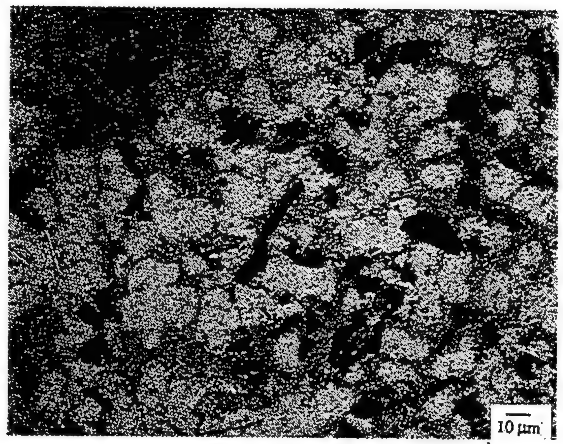

Figure 2. A359 No. 3 optical micrograph showing about 15 vol. percentage SiC reinforcement at 500×.

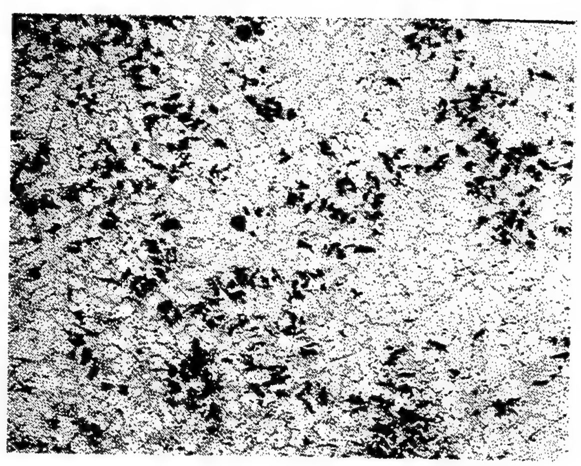

Figure 3. A359 No. 3 optical micrograph showing about 13 vol. percentage SiC reinforcement at 200×.

1.4 Mechanical Characterization. Tensile testing was done at the Naval Surface Warfare Center at White Oak, the University of Delaware, and the ARL-MD Watertown site using American Society for Testing and Materials (ASTM) E-8 testing procedures.

2. RESULTS AND DISCUSSION

2.1 Processing Parameters. Three processing parameters were varied during the MCF process, including dwell time, squeeze pressure, and squeeze duration. The processing parameters for the squeeze-cast aluminum-reinforced metal matrix composites (Al-MMC) are unknown, because of misidentification of specimens during final machining by the APG Metal Shop 1. Therefore, correlation of property data to processing parameters was not possible.

The typical heat treatment of A356-T6 was solution heat treatment at 540° C for 12 hr and then aging at 155° C for 3–5 hr. The A359 MMC specimens were not heat treated, but future test specimens will be heat treated to T6 condition. The typical compositions of the alloys are shown in Table 2.

Table 2. Composition of Matrix Alloys in Weight-Percent[a]

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Others
A356	6.5–7.5	0.20	0.20	0.10	0.25–0.45	0.10	0.20	0.15
359	8.5–9.5	0.20	0.20	0.10	0.50–0.70	0.10	0.20	0.15

[a] R. Davis, Davis and Associates, Editors. Alluminum and Aluminum Alloys. ASM International, Metals Park, OH, 1993.

2.2 Hardness Testing. Hardness measurements were made on the tensile specimen after the tensile tests. The typical hardness for A359/SiC/10p-T6 is 73 HRB while A356-T6 is in the mid-50s HRB as seen in Tables 3 and 4. The hardnesses for A359/SiC/10p and A356-T6 have to be further studied to find the factors that contribute to the lower hardness produced during these tests. (Hardness testing was done on a Rockwell Hardness tester using a 100-kg load with a 1/16-in ball.)

2.3 Metallography. Metallographic specimen preparation for etching A369 entailed swabbing the specimen with Poulton's solution, rinsing in a 50/50 ammonia hydroxide solution, then staining with CrO3 solution. The procedure for etching A356 was swabbing the specimen with Keller's etch, then rinsing in ethanol.

Table 3. Hardness Measurements (HRB) for As-Cast A359/SiC/10p

Specimen	1	2	3	4	5	6	7	8	9	10	Avg.
6	49.9	52.0	51.9	52.1	51.2	49.5	50.8	50.9	50.2	51.0	51.0
7	52.7	54.3	54.4	51.9	56.9	54.0	53.3	54.0	52.8	50.6	53.5
8	52.4	53.5	54.6	76.4	53.9	52.7	51.1	49.9	50.4	—	54.9
10	50.1	51.4	53.8	53.4	53.1	51.8	52.7	53.0	52.6	50.6	52.3
11	53.3	55.7	54.8	56.0	53.9	52.6	—	—	—	—	54.7

Table 4. Hardness Measurements (HRB) for A356-T6

Specimen	1	2	3	4	5	6	7	8	9	10	Avg.
B-2	12.8	28.1	30.3	25.2	24.7	23.4	23.2	—	—	—	24.0
C-1	18.0	22.1	25.4	24.7	19.7	17.4	16.8	18.7	—	—	20.4
G-2	13.5	25.2	13.9	14.0	16.9	19.2	12.8	10.9	—	—	14.6
X-2	14.1	19.9	19.6	16.9	17.0	17.3	14.2	11.8	—	—	16.4
Y-1	12.1	25.0	23.2	24.6	24.1	19.6	18.1	—	—	—	21.0
1-2	24.6	28.4	26.4	24.4	25.1	25.8	32.3	—	—	—	26.7
2-1	11.4	28.1	24.5	25.1	28.4	21.3	22.1	21.0	—	—	22.7
3-2	21.1	21.9	24.1	23.6	21.5	26.8	22.1	—	—	—	23.0
4-1	21.1	23.4	16.8	18.3	16.0	20.9	21.5	23.8	30.7	22.6	21.5
5-1	22.8	22.9	20.8	26.3	27.2	24.4	22.7	—	—	—	23.9

Grain size and dendrite-arm spacing were calculated from the micrographs, and are shown in Table 5. The grain size for the alloys was in the 25–35-µm range, which is shown in Figure 4. The typical dendrite-arm spacing values for cast A356 used for die-cast methods are in the range of 5–15 µm.* Figure 5 shows the typical dendrite-arm spacing of the A356 casting to be around 10–12 µm, and most measurements taken were shown to be in the range for die-cast alloys.

*J. R. Davis, Davis and Associates, Editors. Aluminum and Aluminum Alloys. Metals Park, OH: ASM International, 1993.

Table 5. Grain Size and Dendrite-Arm Spacing Measurements

Bar No.	Grain Size From Optical Micrographs (μ)										Avg. GS (μ)	Est. Dendrite Arm Spacing (μ)
B-2	32	26	26	30	25	30	40	45	40	40	33.4	14.0
C-1	24	44	26	50	35	20	25	40	40	40	34.4	10–16
G-2	30	20	14	40	40	50	25	35	20	35	30.9	8–14
X-2	20	24	26	25	30	40	25	20	55	5	27	12–14
Y-1	34	26	19	40	45	35	20	30	40	20	30.9	10–14
1-2	24	22	18	35	40	50	20	30	25	50	31.4	10–12
2-1	26	22	24	25	35	40	35	35	30	15	28.7	10–12
3-2	18	34	19	30	30	40	35	35	20	20	28.1	10–12
4-1	28	22	22	35	20	30	40	40	20	40	29.7	10–14
5-1	28	20	18	30	30	20	50	35	25	30	28.6	8–12

Figure 4. A356-T6 No. 2-1 optical micrograph showing typical dendrite-arm spacing at 500×.

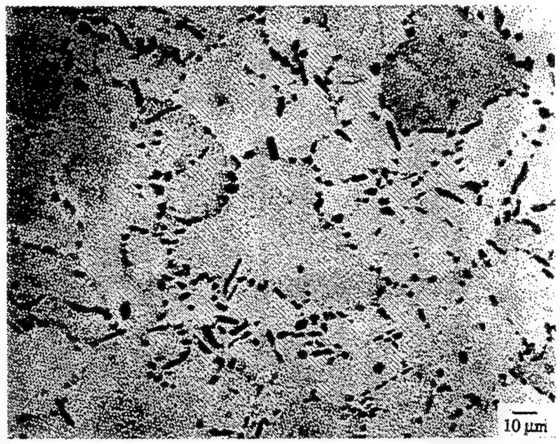

Figure 5. A356 No. 4-1 optical micrograph showing grain size at 500×.

2.4 Mechanical Properties. Tensile testing of the A359/SiC/10p as cast was done on only six specimens and produced only one valid test, due to premature failure of strain gauges and/or fracture in the grip area. Some of the tensile bars were found to have defects traceable to the die lubricant used. The problem has since been solved by using a talc-based lubricant. The mechanical properties comparisons are shown in Tables 6 and 7. The values for A359/SiC/10p are lower than expected for two reasons. First, the test specimens were tested as cast, and found to be deficient in magnesium by chemical analysis. Magnesium is used to increase strength in these alloys, which could help explain why the strength is low in these specimens. The magnesium was probably cooked out of the specimens during the heating of the melt and the casting process. While the strength for the A359 MMC was lower, the ductility was twice that of the typical properties of F3S.10S from Duralcan. The tensile properties for A356-T6 are a little lower than expected, and can be attributed to the fact that magnesium was deficient, as seen in Table 8. The squeeze-casting process did demonstrate superior ductility over conventional casting techniques. A correlation was not found between processing parameters and the mechanical properties. The typical fracture surface features of the MMC are shown in Figures 6 and 7. The fracture surface of the MMC shows a combination of ductile and brittle fracture.

Table 6. Mechanical Properties for A359/SiC/10p

Bar No.	UTS (ksi)	0.2 YS (ksi)	Modulus (Msi)	UTS (MPa)	0.2 YS (MPa)	Modulus (GPa)	El %	C.S. (in/min)
8	32.2	20.9	8.4	222.0	144.1	57.9	2.3	0.004
F3S.10S-T6[a]	49	44	12.5	338	303	86.2	1.2	—

[a] Data from Duralcan datasheet.

Table 7. Typical Mechanical Properties for 356-T6 Alloy Processed by Other Casting Techniques[a]

Processing Techniques	UTS (MPa)	0.2 YS (MPa)	El %
Sand Casting	228	164	3.5
Permanent-Mold Casting	262	186	5.0

[a] J. R. Davis, Davis and Associates, Editors. Aluminum and Alumimnum Alloys. Metals Park, OH: ASM International, 1993.

Table 8. Mechanical Properties for A356-T6

Bar No.	UTS (ksi)	0.2 YS (ksi)	El %	Modulus (Msi)	UTS (MPa)	0.2 YS (MPa)	El %	Modulus (GPa)	C.S.[a] (in/min)
B-1[b]	31.19	16.06	26.4	10.1	215.1	110.7	26.4	69.64	0.05
B-2	31.34	16.07	23.1	11.8	216.1	110.8	23.1	81.36	0.05
B-4	28.72	17.24	6.2	6.1	198	118.9	6.2	42.06	0.05
B-5	31.3	16.1	22	8.8	215.8	111	22	60.68	0.05
Avg.	30.64	16.37	19.43	9.2	211.3	112.9	19.43	63.43	0.05
C-1[b]	31.5	16.53	14.2	17.4	217.2	114	14.2	119.97	0.05
C-2[b]	31.46	16.38	24.2	9.3	216.9	112.9	24.2	64.12	0.05
C-3	31.16	16.12	17	18.6	214.9	111.2	17	128.25	0.05
C-4[b]	32.37	17.6	14.1	14.6	223.2	121.4	14.1	100.67	0.05
Avg.	31.62	16.66	17.38	14.98	218	114.9	17.38	103.25	0.05
G-1	30.97	16.54	12.4	11.2	213.5	114	12.4	77.22	0.05
G-2	29.21	15.95	7.7	14.2	201.4	110	7.7	97.91	0.05
G-3	32.85	17.83	12.1	22.7	226.5	122.9	12.1	156.52	0.05
Avg.	31.01	16.77	10.73	16.03	213.8	115.7	10.73	110.55	0.05
X-1[b]	31.55	16.61	16.3	14.8	217.5	114.5	16.3	102.05	0.05
X-1[b]	27.51	16.89	7.8	11.4	189.7	116.5	7.8	78.6	0.05
Avg	29.53	16.75	12.05	13.1	203.6	115.5	12.05	90.32	0.05

[a] Test done on a 50 KIP Instron.
[b] Shrinkage pores at the grip area.

Table 8. Mechanical Properties for A356-T6 (continued)

Bar No.	UTS (ksi)	0.2 YS (ksi)	E1 %	Modulus (Msi)	UTS (MPa)	0.2 YS (MPa)	E1 %	Modulus (GPa)	C.S.[a] (in/min)
Y-1	30.93	15.86	15.8	10.1	213.3	109.4	15.8	69.64	0.05
Y-2	31.72	16.82	14.1	13.7	218.7	116	14.1	94.46	0.05
Avg.	31.33	16.34	14.95	11.9	216	112.7	14.95	82.05	0.05
2-1[b]	31.53	16.04	24.10	8.80	217.40	110.60	24.10	60.68	0.05
2-2	29.75	16.87	10.1	12.7	205.1	116.3	10.1	87.57	0.05
2-3	31.78	17.2	16.7	12.2	219.1	118.6	16.7	84.12	0.05
2-4	29.7	16.48	10.4	9.7	204.8	113.6	10.4	66.88	0.05
Avg.	30.69	16.65	15.33	10.85	211.6	114.8	15.33	74.81	0.05
3-2[c]	4.84	2.52	12.4	8.3	33.37	17.38	12.4	57.23	0.05
4-1	30.7	15.19	13.9	15.5	211.7	104.7	13.9	106.87	0.05
5-1	30.63	15.94	12.3	13.9	211.2	109.9	12.3	95.84	0.05

[a] Test done on a 50 KIP Instron.
[b] A 2-in 50% extensometer was used for all tests except spec. 2-1. Instead, for spec. 2-1, a 2-in 10% extensometer was used with a strain >0.180 in/in recorded before exceeding capacity.
[c] Broke in the shoulder, therefore, YS, UTS, and RA could not be obtained.

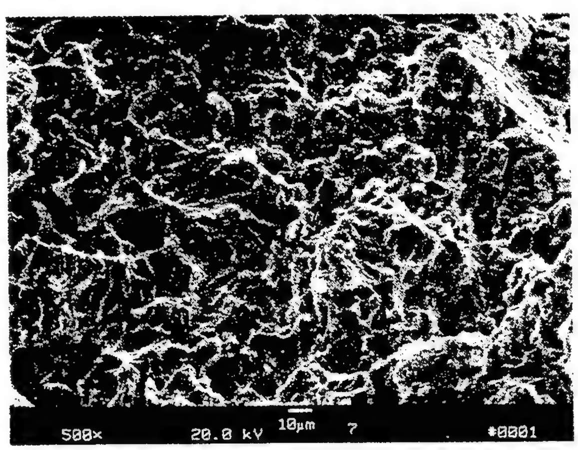

Figure 6. A359 No. 7 SEM micrograph of fracture surface.

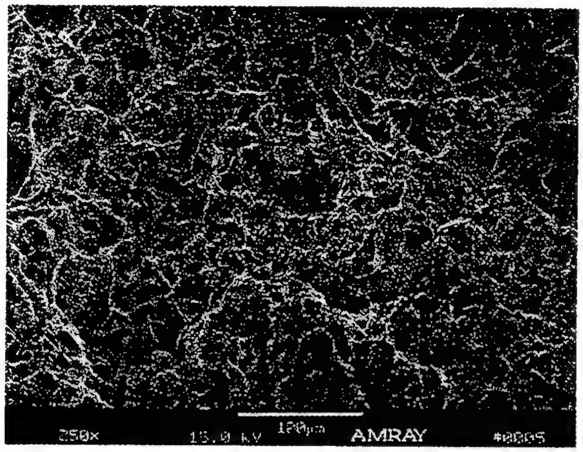

Figure 7. A359 No. 12 SEM micrograph of fracture surface

3. CONCLUSIONS

The mechanical test results did not show any conclusive relationship between the processing parameters (dwell, squeeze pressure, and squeeze duration) and the tensile properties tested. One problem with this new process is the existence of a learning curve. With practice, future runs should produce more homogeneous material with fewer defects. Future tests will also consist of a larger batch size to eliminate statistical anomalies, and allow for the correlation of processing parameters with mechanical properties.

The work in progress has been limited by relocation of equipment on both sides; thus, with the relocation process completed, more progress is anticipated next year.

This year tensile and Charpy V-notch testing along with metallographic studies will be performed.

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13. ABSTRACT *(Maximum 200 words)*

The main driving forces for lightweight materials for the automotive industry and military applications are cost effectiveness, high strength, and wear resistance. Precision Metal Forming (PMF) has developed a new and innovative squeeze-casting process called metal compression forming (MCF). MCF integrates the deceptively simple concept of solidification of metal under direct pressure with closed die forging and low-pressure permanent-mold fill technologies. This hybrid process, therefore, combines the advantages of traditional direct-squeeze casting and low-pressure permanent-mold casting. This report discusses property advantages attained with this process over traditional aluminum casting processes.

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squeeze casting, aluminum, metal matrix composite

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